DEVELOPMENT PLANS FOR A REMOTE CONTROL LABORATORY

DEMONSTRATING THE FARADAY EFFECT

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Development Plans for a Remote Control Laboratory Demonstrating the Faraday Effect

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Abstract

This project presents the design of a physics lab where the Faraday Effect is studied by students in a Remote Control Laboratory (RCL). Background conceptual material for students, equipment lists, lab procedures, and a proposed web interface to the equipment are offered with the design choices supported by research. The final product is a workable demonstration that could be used in face-to-face classrooms or as a laboratory exercise. This project could also serve as a blue print for a future engineering project where the final computer-mechanical-robotic interface could be crafted so that this would indeed become a fully online RCL.

Table of Contents

Introduction

It seems that my academic interests have always hovered near the intersection between science and education. At an early age I was fascinated by the lessons of physics, biology and astronomy. It is also fair to say that much of my interest in science came from watching the Apollo missions successfully land men on the moon and being able to visit educational centers such as the Boston Science Museum. Another influence that affected my outlook on education was my father, a college history professor. I had many chances to observe his teaching style that was mainly Socratic in nature. While he taught only face-to-face classes in history, he continually experimented with different methods to improve his teaching including the use of costumed persona, imaginative *what if* scenarios, and the application of historical themes to current times. I never observed students sleeping in his classes.

My undergraduate degree is in Physics and Astronomy. It has been a long time since I have balanced quantum equations or determined force vectors, but I still retain enough information so that I might be qualified as an expert amateur. When I began my M.Ed. program, I did not have a distinct outcome in mind. I only wanted to improve my professional skills as an Instructional Designer at the University of Alaska Fairbanks (UAF). About four weeks into my first course, Online Pedagogy, I came across an article describing the work of physics instructors at the Kaiserslautern University of Technology. While the article touched on three important aspects of online physics education, I was drawn to the section where Eckert, Gröber, and Jodl (2009) outline a set of design principles that comprise the effective remotely controlled laboratory (RCL). The experiments that the authors reference have been online since 2001, and are still available to anyone with a web browser in the world. These experiments are valid supplements to any first or second year Physics course. After seeing what the authors had done at Kaiserslautern, I knew that I wanted to design an RCL to supplement Physics education at UAF.

Rationale

My question then became *What Physics lab experiment should I create as an RCL?* I drew inspiration from the remake of a television show that had inspired me as a high school student. In 1983, PBS broadcasted Carl Sagan's *Cosmos*. It was an educational series that combined lessons from Astronomy, Physics, Biology, Geology, History, and Ethics. It was ground breaking in its scope, content, and method of delivery. For 13 episodes, viewers were enthralled each week as Sagan delivered rich lessons for about an hour. In 2014, Cosmos 2.0 was unveiled to the world with Neil Degrasse Tyson as the host.

In its second incarnation, Cosmos portrayed the pivotal work of various researchers through history. One of the scientists featured was Michael Faraday. Faraday's work is the mainstay of Electricity and Magnetism, but most people are not familiar with one of his most important discoveries. In 1845 he demonstrated that a magnetic field could rotate the plane of polarization of light. This was ground breaking because it showed for the first time the relation between light and electricity and magnetism.

In order to fully appreciate the significance of Faraday's discovery and understand the logic behind my instructional and physical design choices for the proposed RCL, it helps to be familiar with three concepts from physics: *polarized light*, the *Verdet* constant, and *Faraday Rotators*.

In order to understand what polarized light is, one must understand that light can be described by an electromagnetic transverse wave. In the wave description of light, both the electric field and the magnetic field vectors are perpendicular to each other and the direction of travel. In normal, incoherent light, particles of light, photons, will not necessarily have their electric and magnetic fields pointed in the same direction, but will instead be randomly distributed around the axis of travel. In contrast, light that has been polarized will have its electric and magnetic field closely aligned along a specified angle ("Polarization (waves)," n.d.). This angle can be measured by observing the luminosity of a light beam as it passes through polarization filters. A polarization filter will block nearly all of the light passing through that is oriented perpendicular to the angle of the filter.

Polarized light will have its polarization angle rotated when it passes through a substance subject to a magnetic field. The amount of rotation is proportional to the length of the substance and the strength of the magnetic field. The Verdet constant, expressed in SI units is measured in radians per Tesla meter ("Verdet constant," n.d.). The Verdet constant is unique to a given substance, at a given temperature, for a particular wavelength of light. When studying the phenomena of *Faraday Rotation*, it is useful to study substances with a large or strong Verdet constant so that the rotation of the polarization angle can be observed and measured. Most liquids and glasses have a very small Verdet constant resulting in a rotation angle that is too small to be measured in an undergraduate physics laboratory.

A *Faraday rotator* is a material that allows light to pass through it and has a sufficiently strong Verdet constant such that along the length of the Faraday rotator, the angle of polarization will have a measurably large enough rotation.

Figure 1. Michael Faraday's laboratory at the Royal Institution. His original lab equipment used a silvered mirror to reflect lamp light across a magnetic induction coil and through a grated polarizing filter (Druyan, Sagan, & Soter, 2014).

Unfortunately, this lab exercise reproducing the work of Michael Faraday is not often given to students, even in face-to-face classes. Because it was so important to the development of modern physics, and the equipment list is relatively simple, I believe it to be a perfect candidate for development into an RCL.

The Faraday Effect has relevance in modern research as well. In mid-April of 2015, work was published in *Science* that shows calculations of the incredibly strong magnetic fields near the vicinity of a supermassive black hole in another galaxy. This was the first application using the Faraday Effect to study the environs near black holes, and it will likely usher in renewed interest in existing recorded observations and prompt astronomers to compare other galactic black holes to this first one ("ALMA Reveals Intense Magnetic Field Close to Supermassive Black Hole," 2015).

Another interesting application of the Faraday Effect is in food quality management. Abu-Taha, Halasa, and Abu-Samreh (2013) measured the Verdet constants for a variety of vegetable oils. It turns out that a number of them including premium virgin olive oil, almond oil and wheat oil all have strong magneto-optical properties rivaling the ability of even Faraday's original flint glass to rotate the polarization angle of incoming light. These Palestinian researchers measured several varieties of local oils and determined that each had identifying Verdet constants. They also observed that the magneto-optical properties of the oils would change over time depending on how they were stored. Sunlight reduced the Verdet constant, whereas cool dark storage and normal oxidation increased the Verdet constant. The authors conclude that the Faraday Effect could be used to identify unknown oil types and give an indication of what storage conditions the oils had been subjected to. I found this research because I had trouble locating a good Faraday rotator, and I was attempting to locate a substance that could be used instead of optical glass. It was helpful in two ways. It showed the relevance of this branch of physics in food science, and it provided me with a substitute material that could be studied in the laboratory at relatively low cost.

Another helpful bit of research came by way of Nahrain University in Baghdad. In their paper on specifically measuring the Verdet constant for olive oil the authors show results that olive oil is strongest as a Faraday rotator at a light wavelength of 650nm (Shakir, AL-Mudhafa, & Al-Dergazly, 2013). This is fortunate because it is the color of the most widely used laser in labs, red. Some of the procedures that the authors published helped influence my choices for lab activities in my own project.

Review of Literature

One of the critical components of learning in any of the physical sciences is the laboratory experience. In the lab students get to see theory in action, apply analytical thought, and learn professional practices while recording their observations. One of the constraints to this lab experience, especially at traditional campuses is time. Typically students are limited to lab access for a course for periods extending no more than three hours per week. Most students and instructors agree that more lab time is needed, but there is rarely enough time (Andujar, Mejias, & Marquez, 2011).

This is where RCLs provide the starkest contrast to the traditionally scheduled on-site laboratory. RCLs can be designed for continuous access and allow students multiple return visits and trials at observations should they wish to spend more time observing phenomena or investigating a process (Gomes & Bogosyan, 2009). Of course with a much longer operating period when compared to face-to-face labs, RCLs tend to cater to the more independent learners who seek their education via distance learning (Feig, 2010).

While hands-on lab experience, traditionally delivered in on-site labs, is vitally important to the core of the physical sciences curriculum, it comes at a steep price. Factors such as development, maintenance, storage, required staffing and scheduling make the prospects of operating laboratory space a costly one. Contributing to these factors is the recent upward trend in enrollment of students seeking degrees in engineering and natural sciences. Higher enrollments of students require additional lab space, at least if offered with traditional means. RCLs can extend lab access beyond normal academic hours and can optionally be used to enrich, rather than replace, the physically spaced lab (Gomes & Bogosyan, 2009). RCLs can relieve some of the constraints of scheduling that face-to-face labs present (Abdulwahed & Nagy, 2009).

Yet another cost influencing factor exists with laboratories mainly used by researchers. Experiments and facilities are getting more complex and expensive to construct and operate. One effort that can at least leverage a wider range of funding sources is to provide dual use for constructed RCLs between research and teaching. This is true in the realm of magnetic fusion experiments where interested researchers are located around the globe, and the need to train students is not bound by any political or institutional boundaries (Schissel et al., 2009). Inherently RCLs are capable of providing collaboration between lab partners or researchers who are not in the same physical location (Bates, 2013). RCLs also provide the possibility of training with international colleagues, a skill that is valuable in many scientific careers (Ku, Ahfock, & Yusaf, 2011).

There is a sustained need for professional training in the ranks of nuclear weapons and facilities inspectors who are able to receive top-notch training from the Nuclear Engineering Teaching Laboratory (NETL). NETL is associated with the University of Texas at Austin. Students from the International Atomic Energy Agency and the U.S. Nuclear Regulatory Commission are able to take a variety of nuclear related courses with RCL access to the NETL reactor (Tipping, 2011). The RCLs offered by NETL also keep student experimenters at a safe distance from deadly radiation. RCLs offer the best possibility for research and learning when materials are hazardous or otherwise unavailable (Sajo-Bohus, Greaves, Barros, Gonzalez, & Rangel, 2007).

Hazardous materials are not the only limiting factor in getting people into the physical presence of laboratory environments. At the present time, it is impractical for researchers or students to travel to Mars or locations even further out in our solar system. But people have grown used to the fact that we can get images from the red planet that are only twenty minutes old. The Mars rovers represent RCLs extending our abilities in two ways: They provide us with images and data from environments that we cannot for the moment get to, and when coupled with a robust archival process, the data collected by the rovers or any other space platform become available to future researchers (Maki et al., 2012).

Of course the distance between the lab and the student do not have to cover the span of planetary orbits, in order for RCLs to be cost effective. In countries such as Australia and Canada, and in states like Alaska, RCLs can eliminate or reduce travel budgets and can make a rich laboratory curriculum possible where it would otherwise be cost prohibitive. In order to leverage RCL infrastructure to an even larger degree, some learning institutions are banding together to share lab resources and the burdens of development (Ku et al., 2011). This equipment sharing is practiced on an informal and organic level as well. Baran, Currie, and Kennepohl (2004) note that after setting up an RCL in Alberta, Canada, the same equipment used for research was soon able to be used by students and lecturers in New Zealand.

RCLs, more than simulations or virtual labs, tend to lead to rich discussions, analysis and reflection. Because data derived from real apparatus, even from a distance, will contain statistical variations, students and instructors will have the opportunity to determine what were the factors causing the variances (Jona & Vondracek, 2013). Variations in the data combined with the open accessibility of the RCL, prompt some students to use the RCL more than once, to engage the equipment longer than they would with simulations, and to produce higher quality reflections (Sauter, Uttal, Rapp, Downing, & Jona, 2013).

In one study conducted at Bordeaux University, French electrical engineering student reactions to virtual and remotely controlled laboratories were taken into account, along with assessments of their learning outcomes. What was interesting in part were some of the comments generated by the students who requested more web cams of the circuits they were studying. The students believed that the web cams were essential in reinforcing that what they were working on was real, as opposed to a model (Lang et al., 2007).

At some point teachers and instructional designers must consider the pedagogy and actual design factors that contribute to a good RCL and hence a solid learning outcome. Writing in the *American Journal of Distance Education*, Eckert et al. (2009) list their first criteria for a good RCL to be that a proper experiment should be chosen. By proper, the authors stress that a study should be taken that does not always perform flawlessly. The message is that through analysis and reflection of unexpected results, students will develop a richer understanding of the topic. Second, the person interacting with the equipment at a distance should be able to see what is going on, with the aid of web cams.

The third design factor, in the development of RCLs that Eckert et al. (2009) share, is that the controls of the experiment should be intuitively clear. The controls should be easy to operate, without the need for reading manuals. Fourth, the user must be able to retrieve his data via the Internet. When possible the student should be allowed to perform further analysis and processing on the collected data. Fifth, if it is desired that the RCL always be available, then the equipment in the lab should be simple and robust enough to handle long periods of time without any human intervention.

Eckert et al. (2009) list their sixth priority to be that any background information should be readily available to the user of the RCL, on the same web site. They specifically indicate that additional textbooks should not be required to interact with the RCL. In order to gain the interest of the user, the authors specify as their seventh recommendation, that there should be a multitude of options available for study, and that these options should be made available to the user through the use of the control interface. Their eighth and last bit of advice is to make the RCL free and without charge.

Eckert, Gröber and Jodl (2009) were not the only authors who proposed a set of design principles for RCLs. In *IEEE Transactions on Education*, Cagiltay, Aydin, Kara and Alexandru (2011) compiled a list of seven rules after studying student preferred interactions with a remote radio frequency laboratory:

1) Tailor instructions to be appropriate for the user group.
2) Support both linear and nonlinear presentation of content.
3) Limit the number of verbal instructions.
4) Display content in various forms, such as figures, animation, and video.
5) Include interactive content such as exercises and experiments.
6) Limit text-based content and the need for extensive reading.
7) Provide a useful feedback system.

(Cagiltay, Aydin, Aydin, Kara, & Alexandru, 2011)

The second principle speaks to a general criticism of science labs in general: Labs are presented as tightly scripted procedures that students follow along without much input. It is as if the students are to follow a recipe, with an expected outcome. It is the student's responsibility to ascertain, only at the end of the experience, why he as fallen short of what theory predicts. What is missing according to Peters (2005), is the idea that the students set out to investigate or observe something just as professional scientists do in the field or laboratory. Peters lists several suggested fixes in the forms of small changes that instructors can do to change the lab from what he labels as *cookbook labs* to a model based more on *inquiry learning*. The idea of not providing the students a complete procedure is offered in several variations with the intent that the students will have to become more actively involved in the lab, hopefully engaging higher-level thinking.

Van Der Meij (2007) explains that the amount of information provided to students in a computer interface is key to their motivation. The author posits that students are most motivated to learn something while they are performing a task that requires that specific knowledge. Right at the moment that the student has a need to know the knowledge is the best time to provide them any background theory needed to complete an exercise. Van Der Meij proposes two tactics that provide the best learning outcome: minimalism and ECOLE or *Emotional and COgnitive aspects of LEarning*. The later approach plays off student feelings of interest in learning itself, and the rewards associated with completing goals. Another idea the author details is that the student should be comforted in the knowledge that they will make mistakes, that making mistakes is expected, and that the student can successfully get back to completing the learning goals.

Van Der Meij referenced an earlier work by Carroll and Rosson (1987). *In The Paradox of the Active User,* Carroll and Rosson write about students needing to learn by doing, and that at times they are unable to proceed on a task until they grasp a concept. Laboratory Science is active learning. Sometimes students will have been introduced to a concept in a lecture or a text, at other times a lab exercise is their first exposure to the new idea. What Carroll and Rosson suggest in terms of designing instructional interfaces between humans and computers is to place the needed information as close to the area of activity as possible.

Physics by most accounts is not an easy subject. Contributing to the *2008 Physics Education Research Conference,* Sabella, Coble, and Bowen (2008) presented work and new teaching practices conducted at Chicago State University (CSU) that tended to create a better learning environment for students. One of the observations that physics instructors at CSU have made is that even though students can retain formal physics concepts, they sometimes rush to answer a question or approach a problem intuitively. There are many concepts in physics where novice intuition runs counter to physical reality. This is especially true in branches of physics such as relativity and quantum mechanics. The practice employed by instructors at CSU is to quickly challenge wrong answers and approaches. When this is done the student can recall and employ their *correct formal knowledge* to solve a problem.

Statement of Bias

One major choice I am bringing to the design of this RCL-based project is the philosophy of open standards and vendor agnostic requirements on the student side of the RCL experience. As it pertains to the machine and software requirements for a student's computer or mobile device, the RCL should not require specific operating systems or browser applications. This is in line with the approach taken by Eckert et al. (2009), where the authors conclude that what makes part of a good RCL experience for students is not being burdened by specific software requirements on their end. On the experiment side of the RCL experience, I believe that wherever feasible, open source software and readily available hardware solutions should be used, rather than specific use hardware/software combinations. This is reflected in an earlier publication from Kaiserslautern where Gröber, Vetter, Eckert, and Jodl (2007) indicate their preference for open source systems so that the designs can be shared with and built by other instructors around the world, with materials that they have access to.

This is not the approach taken by some RCL initiatives. The North American Network of Science Labs Online (NANSLO), an initiative of the Western Interstate Commission for Higher Education (WICHE), has several online activities and more planned for review. NANSLO's labs deviate from the design philosophy of the Kaiserslautern University labs in several ways.

Notably, users of the labs must first install various bits of software on their computers in order to be able to run the experiments. Mobile devices are not supported at this time. In addition to this initial barrier, a student must belong to a registered class of a participating and funding institution in the NANSLO program. The instructor of a class must first provide NANSLO a roster of students and schedule blocks of time where expected student activity is to occur. Subsequently students must visit a separate website, login there, and schedule lab time (*Scheduling a Lab - Students | Western Interstate Commission for Higher Education, 2015*).

It is interesting that NANSLO is evolving its approach. As late as November 2014, they required students to use the Windows Operating System in order to access their online labs. They have taken a step toward vendor neutrality by now requiring Citrix Software that lets you essentially share the screen of a remote computer. It is bandwidth intensive in requiring 5Mbit/sec broadband speeds, and it does not run on any mobile devices.

The NANSLO experience is different and inferior even without these considerations. One of the most fundamental activities of any lab exercise is measuring data. Rather than provide students with a webcam view of their remote lab instruments, key data values are merely displayed in text panels in a computer UI dialog box. This removes the student from truly understanding the physical limitations and parameters of the measuring device and eliminates the skills associated with calibration and interpolation.

The advantage of using proprietary software, scheduling and remote lab assistants, like NANSLO employs, is that certain experiments are easier to set up. The disadvantage of using proprietary and generic lab software that is fitted to a given exercise is that the student must spend time sifting through a foreign interface that has nothing to do with the scientific principles demonstrated. As Eckert et al. point out, “The use of an RCL via the Internet must be intuitively clear and the user should not be forced to read a detailed manual” (2009, p. 133).

The University of Coimbra (Portugal) begins with a faulty approach. One of the introductory web pages for potential users reads, "To use the RVL, the user should log on in the platform’s website and go through the requirements verification page to investigate whether he/she has the required software"(Cardoso, Vieira, & Gil, 2012). My view is that students should be investigating scientific principles not whether their Internet device is able to jump through technical hoops on a web site. This is an example of poor design.

Methods: Design of the Project

Shortly into the development process I discovered that what I expected to be an easy process became a moderately difficult task. After receiving an adaptation of Michael Faraday's magneto-optical effect lab, I had originally planned on using the following lab components as prescribed in *The Art of Experimental Physics*:

- Monochromatic collimated light source (laser or white light with monochromator)
- Laboratory electromagnet (bored axially with at least 0.5T capability)
- Gaussmeter
- Photodiode or phototube detector
- Light and heavy flint glass (prisms and rectangular blocks)
- Two polaroid filters (one of which can be rotated)
- Prism spectrometer
- Mercury vapor lamp

• Oscilloscope and motor (Preston & Dietz, 1991)

Most of the equipment was available to me for use through the Physics Department at the University of Alaska Fairbanks, but one critical item that was not present was the heavy flint glass. I soon learned that flint glass is not readily available, and where it can be found it is costly and has a back order time of weeks. I placed an order for an appropriately shaped block only to find out weeks later that the company was out of stock and could not deliver until some time in early June of 2015. I was in the position of trying to develop a lab on the Faraday Effect without having a Faraday rotator.

One benefit of having access to the undergraduate physics labs at UAF was also having access to the woodshop. I was able to construct some rudimentary optical stands and height adjusters from scrap plywood. I was also able to repurpose a metallic crown from one of the UAF Physics 211 Archimedes labs that seemed to be a perfect holder for the photo-receptor.

In late March 2015, I still had no Faraday rotator. In order to see any sort of *Faraday Effect* one has to have a combination of a strong magnet and a good rotator. I was not sure that I had either. With some estimation I learned that the current generator available to me was only able to provide about 50% of the current I needed. That meant I needed to use a Faraday rotator that was twice as strong to have the same resulting angle of rotation I was looking for, which would appear as a rotation of about 20 degrees and be a significant experience to observe, either in a classroom demonstration or a physics lab.

After finding the relevant publications on the Verdet constants of olive oil, I began looking for ways to hold a sample of oil inside of a solenoid that would permit a laser to beam through. The proper piece of lab equipment for such an endeavor is called a cuvette and resembles a miniature above ground oil tank that is found outside of many homes in Fairbanks, Alaska. The cuvette's main features are that the faces of the cylinder are polished and transparent allowing a researcher to fill it from the side without the liquid spilling.

I was surprised to find that with the stoppers in place to hold the olive oil, the cuvette would no longer fit inside of the solenoids that were present in the lab. I needed to construct a larger solenoid coil. My first attempt at a coil involved purchasing some bulk wire from a local hardware store. The initial solenoid I had was limited to a continuous supply of 5A. Even with this current flow, the wires soon became very warm to the touch. In my construction plans I opted for thicker wire that in my mind, would allow for more current. The world of physical reality does not share much with the world of conceptual diagrams and mathematical equations, at least not in practice. Although I was able to deliver 14A continuously to my newly constructed coil, my constructed solenoid had fewer turns due to the fact that the wire was bulkier and impossible to have as many loops in the same space as the original thinner wire. The measured field was less than the original coil, but at least I was able to fit the olive oil filled cuvette inside of the coil.

My next challenge was discovering that my new solenoid still grew quite warm with only 10A current flowing through it. It grew warm enough that it began to transfer heat to the olive oil in the cuvette. I discovered that as the olive oil changed temperature, so did numerical value of the Verdet constant of the olive oil. This is because the Verdet constant is temperature dependent. I soon adopted the practice of turning on the current only for a short while, a span of 10 seconds at a time, while I let the photo-receptor collect laser light samples. I had one final idea towards mid April 2015, and that was to use a slightly smaller gaged wire still in its original factory spool. Figure 2 shows the last version of the equipment I used to record my observations and it shows all the equipment except for the power supply and the desktop PC which collected the aggregate data from the photo-receptor.

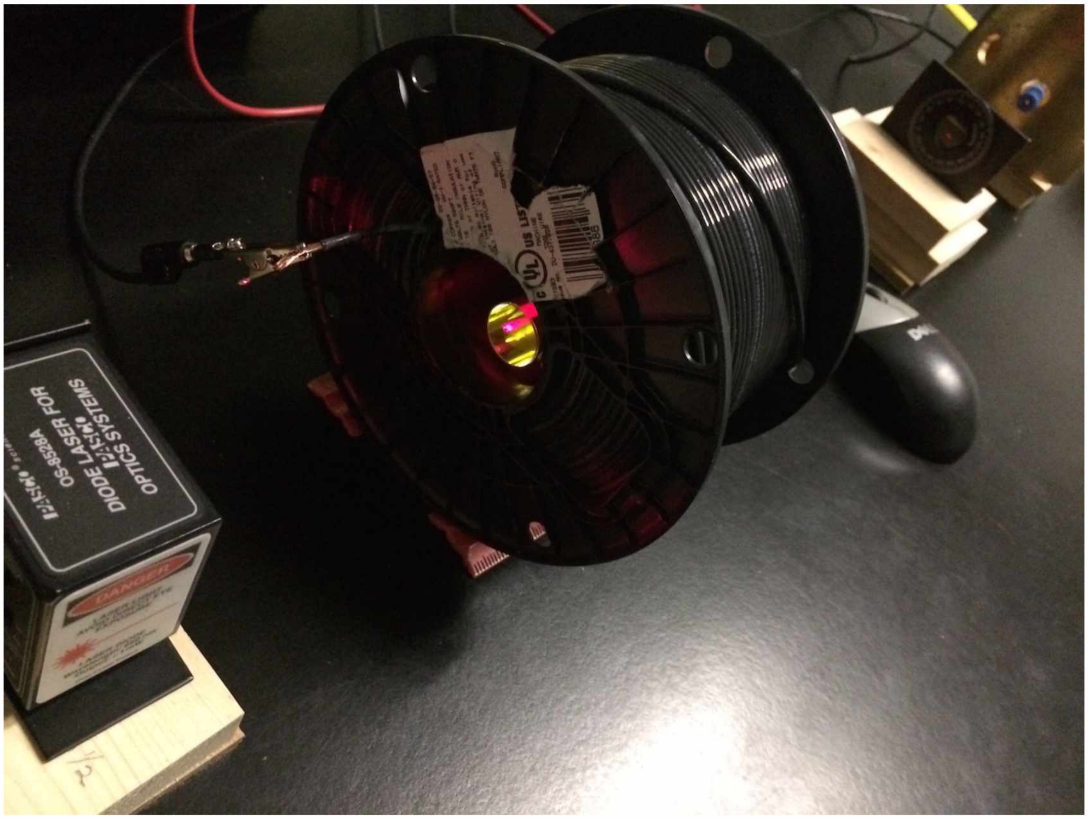


Figure 2. The 650 nm red laser at lower left shines toward the solenoid (wire spool) and through the olive oil filled cuvette (center of wire spool). Beyond the spool an in the upper right of the photo is the polarizer which can be freely rotated to any arbitrary angle. The photo-receptor is in the extreme upper right of the photo (where the beam's final intensity is measured).

I began to record data and it is presented as follows:

Appendix A: brightness of laser versus polarizer, without field or rotator.

Appendix B: brightness of laser versus polarizer angle, through olive oil media with and without a magnetic field B induced by 10A through my solenoid coil.

After analyzing the recorded data, I realized that I was observing a very weak Faraday Effect. I would estimate that I was able to rotate the angle of polarization of the laser by roughly 1.0 degree. Further numerical analysis could reveal a more precise answer but I knew that with the materials and equipment on hand, this would not be an effective instructional lab as it existed. I was extremely careful with my procedure and it took me about 40 minutes to record the data from all the angles of the polarizer. In order to make this a better learning experience for students in an RCL, I needed to obtain a stronger magnetic field, Faraday rotator, or both.

Lab Interface, Instructional Plans, Sample Reports

The main product of this project is a web site consisting of four sections: theoretical background, lab equipment, lab procedures, and a suggested user interface to robotic equipment which would run the actual Faraday Effect RCL. I wrote the content for the pages, created instructional design, and wrote the HTML and CSS which display the pages on the web. I have included the web pages below, but it should be noted that they do not appear the same as they would in a web browser. Print media is different than screen media. The behavior of complex web pages written in HTML 5 and CSS 3.0 for a computer screen or mobile device cannot be reproduced on paper. I did design an alternate set of style sheets for print media. In order to see the web pages as they are intended, they should be visited at:

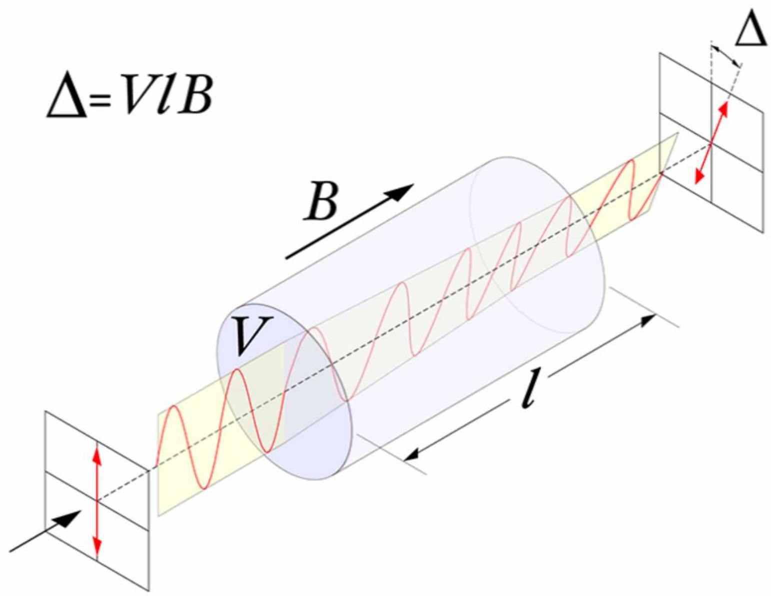
http://onidan.lasota.org/faraday/faraday_theory.html

UAF PHYSICS - ONLINE LABORATORIES
University of Alaska Fairbanks

theory
equipment
procedures
lab

Visually, Faraday Rotation can be conceptualized below. Incoming light at a single wavelength enters from the left. Imagine that it is polarized nearly vertically (zero degrees). It enters a substance that is ℓ meters in length and with a Verdet constant of V. Along the direction of travel the magnetic field strength is B Teslas.

The resulting rotation of the polarization angle is Δ:



Conceptual diagram of a beam of polarized monochromatic light. If it passes through a substance with a known Verdet constant, length and applied magnetic field strength, the rotation of its angle of polarization can be calculated. [3]

Figure 3. This screenshot from http://onidan.lasota.org/faraday/faraday_theory.html shows part of the content that would be presented to a physics student so they would be able to adequately comprehend the theoretical background of the RCL. Note that in this screenshot, the left-hand navigation bar, blue UAF header and background image are present. These design elements are not shown in the printed copy of the web pages included below but are included here for reference.

The Faraday Effect - Theory

Introduction

In 1845, Michael Faraday in his laboratory at the Royal Institute, discovered the magneto-optic effect. He observed after trying many subjects as media, that polarized light traveling through a substance which is exposed to a strong magnetic field will have its plane of polarization rotated. This effect was later named after him: The Faraday Effect.

From Cosmos 2.0, 'The Electric Boy', Michael Faraday applies current to an electromagnet applying the magneto-optic effect on a piece of flint glass, which in turn changes the angle of the plane of polarization of a light beam. [1]

The importance of this discovery is that it demonstrated for the first time a relation between light and electricity and magnetism. The amount of rotation of the plane of polarization depends on three things: the magneto-optical properties of the material that the light traverses, the length of the path of travel through the material, and the strength of the magnetic field.

In addition, the magneto-optical properties of a substance are dependent on the wavelength of the light and the temperature of the substance. A single value can be attributed to the magneto-optical properties of a material at a given temperature acting upon a specific wavelength of light.

Questions:

1. Under what circumstances might the temperature of a substance **NOT** remain constant?
2. What difficulties would this present in trying to assign numerical values to the magneto-optical properties of a substance? Or in measuring the angle of rotation?

The magneto-optical properties of a substance at a given temperature and interacting with a given wavelength of light is called the Verdet constant.

In mathematical terms, the angle of rotation is equal to the product of the Verdet constant, the length of the material, and the strength of the magnetic field. [2]

Equation

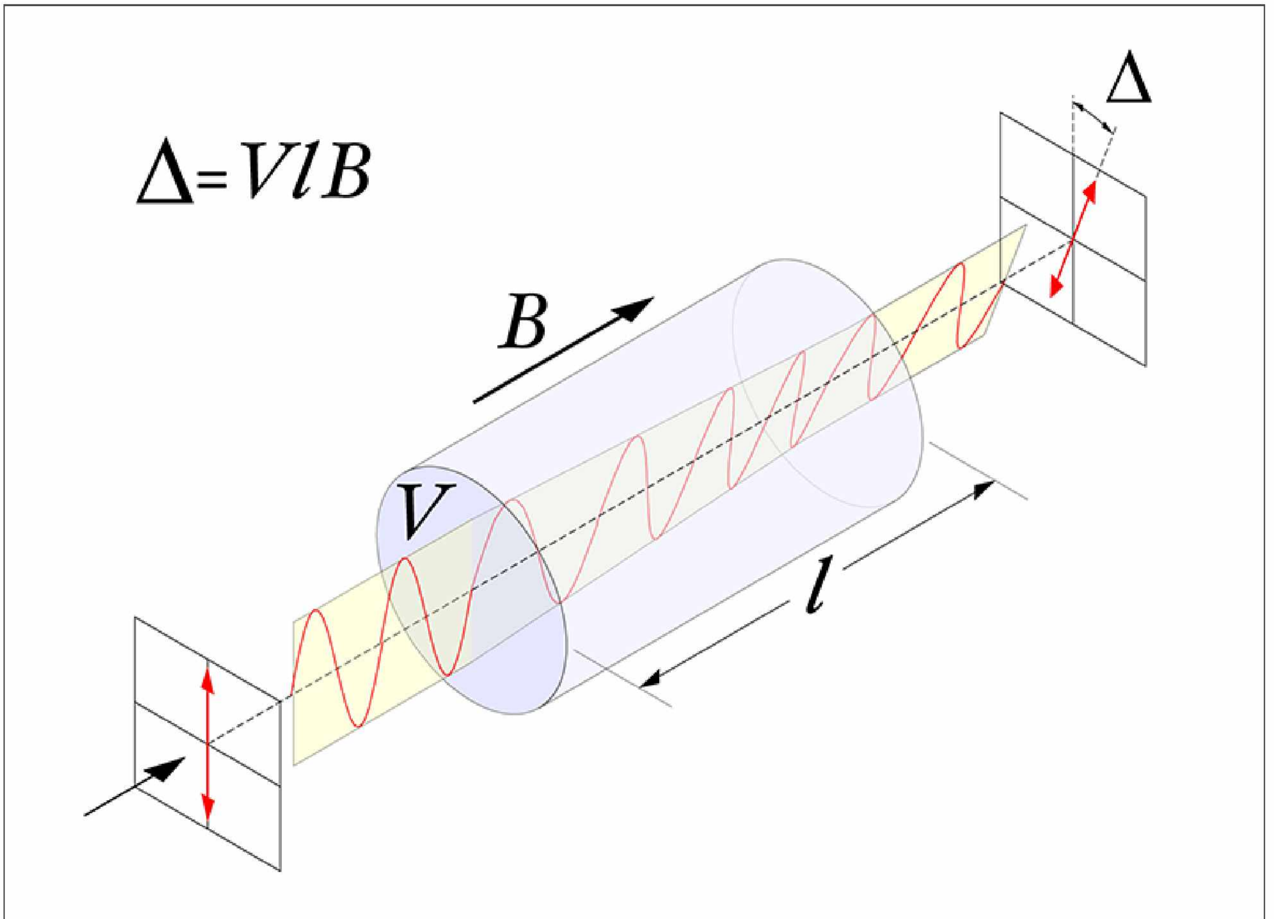
This can be expressed as:

$$\Delta = V\ell B$$

Δ	radians (rad)	the angle of rotation of polarized light
V	radians per Tesla meter (rad)/(T)(m)	the magneto-optical property of the substance for a given wavelength of light and temperature is named after the French physicist Émile Verdet.
ℓ	meters (m)	the length of the substance
B	Tesla (T)	the strength of the magnetic field parallel to the direction of light travel

Visually, Faraday Rotation can be conceptualized below. Incoming light at a single wavelength enters from the left. Imagine that it is polarized nearly vertically (zero degrees). It enters a substance that is ℓ meters in length and with a Verdet constant of V. Along the direction of travel the magnetic field strength is B Teslas.

The resulting rotation of the polarization angle is Δ:



Conceptual diagram of a beam of polarized monochromatic light. If it passes through a substance with a known Verdet constant, length and applied magnetic field strength, the rotation of its angle of polarization can be calculated. [3]

Questions:

3. How would you approach calculating the angle of rotation for light traveling through different layers of several substances (assuming everything else was constant)? Consider, for example, a stack of glass plates with different optical properties.
4. What happens to a light beam that travels through a substance with blended wavelengths?
5. Suppose that you have a lab apparatus with known physical parameters of Δ, V, ℓ, B. If you doubled the magnetic field strength, what would happen to the angle of rotation?
6. By what measure would you have to increase the field strength in order for the angle of rotation to come full circle?
   (That is, an angle measuring $\Delta + 2\pi$ radians) ?
7. Can you think of a procedure you could employ that would determine if the angle of rotation was simple, or a multiple addition of 2π?

Applications

Besides the historical significance of Michael Faraday's discovery, the study of the Faraday Effect allows for many interesting investigations. Here are just a few:

- Physicists in Palestine and Iraq have discovered that certain kinds of premium virgin olive oil have characteristically high Verdet values. They have developed methods to measure the Verdet constants of samples of olive oil to determine their place of origin, shelf life, storage conditions and authenticity. [4][5]
- Astronomers at the European Southern Observatory have used the Faraday Effect to determine the magnetic field strength near the vicinity of super massive black holes in other galaxies. [6]

Question:

8. Consider that some materials are opaque to light in the visible spectrum. Can you think of any applications involving non-visible light, such as x-rays?

References

[1] Druyan, A., Sagan, C., & Soter, S. (2014). The electric boy. In Cosmos: A spacetime odyssey.

[2] Suchat, S., Viriyavathana, P., Jaideaw, P., Haisirikul, N., Kerdsang, W., & Petcharavut, S. (2011). Progress in electromagnetics research symposium proceedings. In Measurement of the verdet constant in different mediums by using ellipsometry technique (pp. 803-806). Suzhou, China.

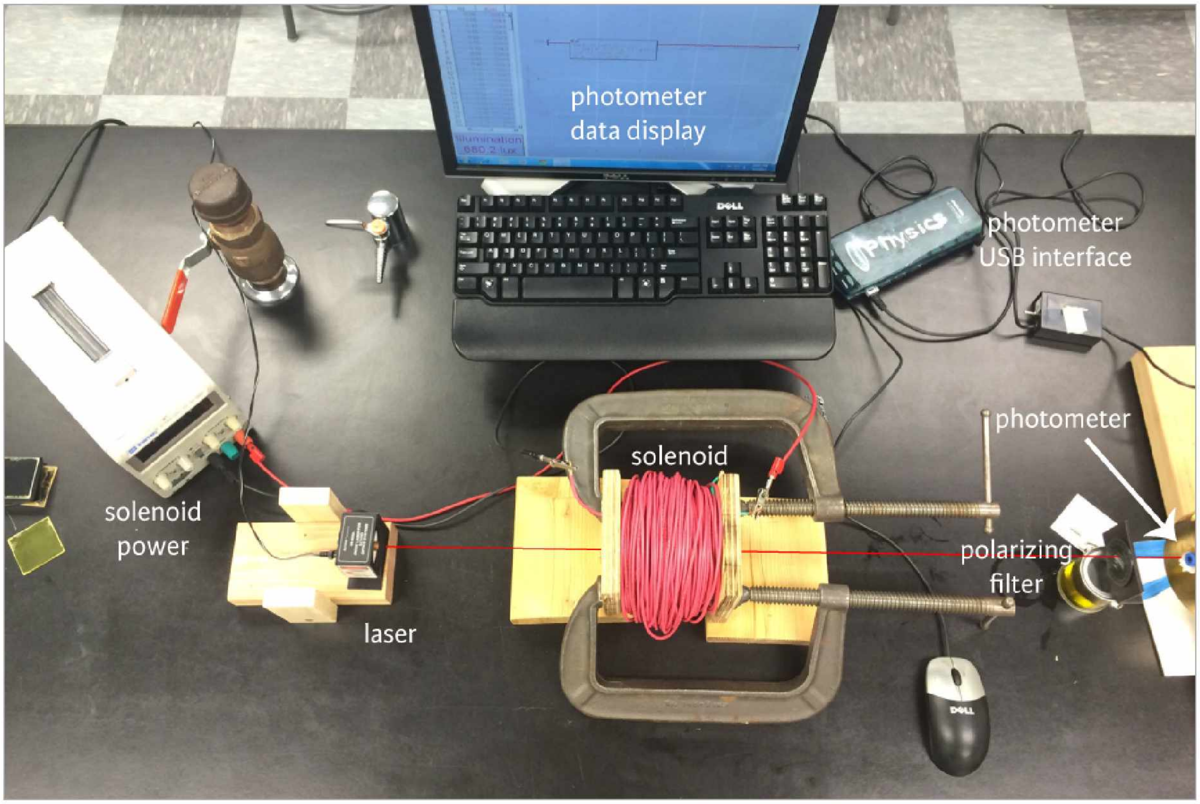
[3] Adapted from an illustration on wikipedia.org, http://en.wikipedia.org/wiki/Faraday_effect#/media/File:Faraday-effect.svg

[4] Abu-Taha, M. I., Halasa, M. A., & Abu-Samreh, M. M. (2013). On the usage of the faraday effect as an authentication technique for vegetable oils. Journal of Modern Physics, 04(02), 230-235. doi:10.4236/jmp.2013.42032

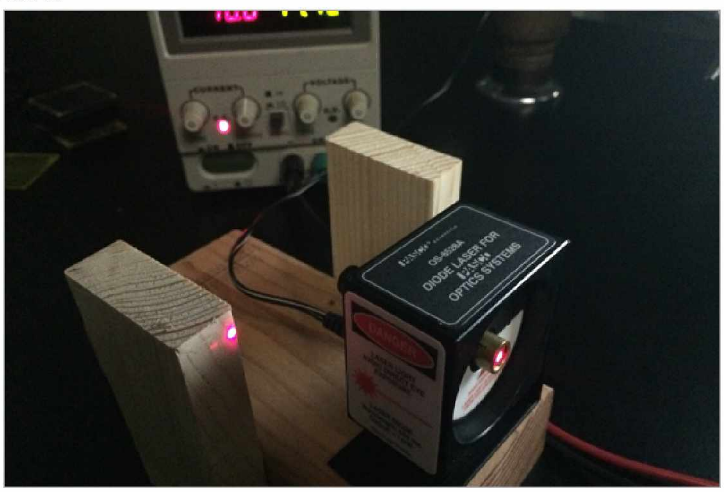
[5] Shakir, A. A., AL-Mudhafa, R. D., & Al-Dergazly, A. A. (2013). Verdet constant measurement of olive oil for magnetic field sensor. International Journal of Advances in Electrical and Electronics Engineering, 2(3), 362-368. Retrieved from http://www.sestindia.org/volume-ijaeee/.

[6] ALMA Reveals Intense Magnetic Field Close to Supermassive Black Hole. (2015, April 16). eso1515. Retrieved from http://www.eso.org/public/news/eso1515/

The Faraday Effect - Equipment



Laser



The laser is optimal for this lab in that it produces monochromatic polarized light at 650nm (red). It also produces steady illumination which is critical for the success of the lab, because we will be studying variations in the luminosity of the beam as measured by the photometer at the other end of the experiment.

Solenoid

The solenoid is a coil of insulated wire, forcing current to wind its way round and round the loops. When current flows, a magnetic field is created. The stronger the current and the more loops there are, the stronger the field. The field will point down the tube (middle of the coil) either to the right or left, depending on the direction of the current through the wires. Because we are trying to measure only the affected angle of rotation, it does not matter which direction the current flows and hence the field points. The angle of polarization will be measurable as long as the product of the Verdet constant and the magnetic field strength is great enough.

Solenoid Entrance

The entrance to the solenoid tube shows the cuvette resting inside the coil. It is filled with olive oil nearly to the top. The point of impact of the laser beam on the optically transparent sides of the cuvette are important to note. There should not be any smudges or foreign material that disperse the laser light. If the cuvette is handled it is important to clean the end faces with special lens cleaning paper. Also note that there are several reflections inside of the solenoid. Each time the beam crosses a media transition (air to glass, glass to olive oil, etc) there is a partial reflection of the beam and the transmitted illumination decreases. In the first picture of the equipment two partially reflected laser spots shine on the power supply for the coil and on a wooden support for the laser.

The red wire near the top left carries current through to the coil.

The inside of the coil is made from common 2 in. inner diameter PVC plumbing pipe which can be found in most hardware stores.

Solenoid Exit

The exit green wire can be seen in this picture and connects the end of the solenoid back to the power supply. The point of exit of the laser beam can also be seen leaving the cuvette.

The large screw clamps hold the wooden support braces together for the solenoid and are present only for structural support.

Polarizer and Photometer

The polarizer can be accurately set to two degree increments and is used to determine at what angle the already polarized laser beam is set. When the filter is set at an angle orthoganal to incoming light most of the light is attenuated. By rotating the filter and noting at what angle the minimum illumination occurs, one can determine the incoming angle.

The photometer shown in the background of this picture is a solid state photo recepter. It is capable of measuring the brightness over regular intervals as narrow as 5Hz. The photometer is set to measure the luminosity at a rate of 200 times per 10 secs, or at 20Hz. This gives a sample size of n=201 and provides statistically sound data.

The Faraday Effect - Procedures

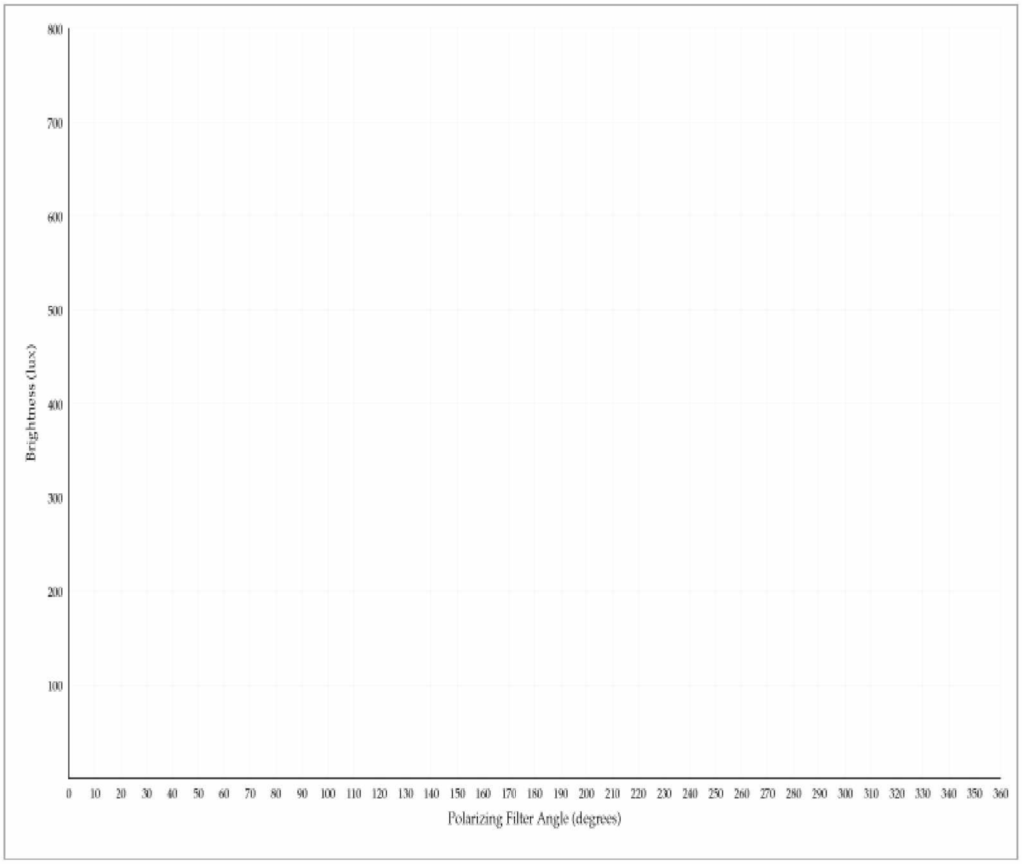
Background

You may want to be familiar with the theory of the Faraday Effect and see what equipment you will be working with. Once you are ready you can use these procedures to investigate the Faraday Effect on the lab controls page.

Determine the Natural Angle of Polarization

Because of the way diode lasers are constructed, they emit polarized light. You will determine the angle that the laser beam is polarized to before being rotated.

1. Align the laser so it passes though the polarizing filter.
2. Align the photorecepter and adjust the scale on the Vernier USB interface so that the lumination reads 770 lux.
3. Adjust the ambient room lighting as dim as possible, and take steps to ensure that the lighting in the room will remain constant during the time you record data.
4. Set the polarizer to 0 degrees. Record the light reading.
5. Set the polarizer to 10 degrees, and record data. Repeat in 10 degree intervals.
6. Plot the light intensity of the laser versus rotation of the polarizer in degrees.



Blank graph to plot values of brightness versus polarizer angle. Larger, printable version available.

Questions:

9. From the graph, at what angle(s) are the brightest readings taken?
10. What about the dimmest?
11. What simple function does the graph look like?
12. What would you expect the graph (and your data) to look like if you rotated the laser on its side?
13. Because of the nature of the data, are there certain angles of rotation that are more interesting to observe than others? Why?

Rotate the Laser 45 Degrees and Measure Brightness Versus Angle

1. Using braces, or a rotator for the laser, rotate it from its normal upright position by roughly 45 degrees.
2. Carefully align the bean so it passes through the polarizing filter and onto the photometer.

3. Again, starting with the polarizer set to 0 degrees, measure in 10 degree increments until you complete data points up through 360 degrees.
4. Plot your measurements on the same graph as above.

Questions:

14. By how many degrees is the minimum point (dimmest) on the first graph shifted in the second graph?
15. What else did you notice?
16. Suppose that you could not see the laser, but only measure the polarizing filter and the brightness via the photometer. Would you be able to tell the difference between the laser in its original position and it rotated upside down (180 degrees)? Why, Why not?
17. What is the precision of your measurements?

Determine the Variance in Brightness Due to Polarizing Filter Placement

1. Set the laser to an upright position.
2. Rotate the polarizing filter to 45 degrees and take a brightness measurement.
3. Remove the filter from the path of the beam and take a measurement.
4. Without rotating the filter, place it back in the beam and take another brightness measurement.

Questions:

18. Are the two measurements the same?
19. How does the difference in brightness compare to your estimated precision?
20. If your brightness level has changed significantly, what changed to cause the difference?
21. What could you do to minimize or eliminate any differences during measurements?

Apply a Magnetic Field Along a Portion of the Path of the Laser Beam

1. Measure the distance along the inside of the solenoid.
2. Set the solenoid so that the laser beam must travel through its inside before hitting the polarizing filter.
3. Connect the solenoid to a power supply. Adjust the current and voltage so

that there are 5A flowing through the solenoid.

4. With the laser in the upright position, and the polarizing filter at 45 degrees measure the brightness of the beam at the photometer.
5. Turn the current off. Take the brightness reading again.

Questions:

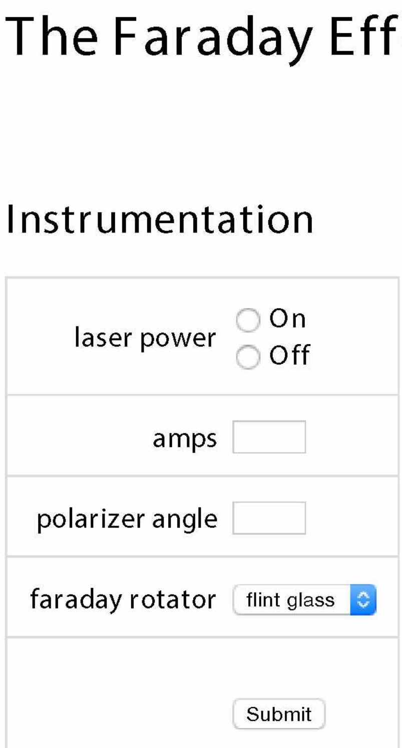
22. What are your two measurements? (For current on/off?)
23. What would you estimate the field strength (in Teslas) to be?
24. Explain the outcome.

Apply a Magnetic Field with a Faraday Rotator to the Beam

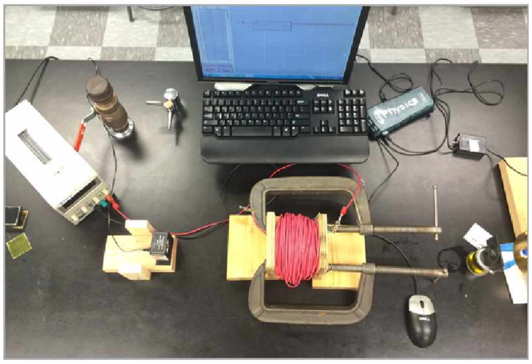
1. Measure the length of the cuvette filled with olive oil.
2. Place the cuvette inside the solenoid and ensure that the beam passes cleanly through, traveling to the polarizing filter and then to the photometer.
3. Apply current (5A) to the solenoid and measure the brightness with the polarizing filter set to 45 degrees.
4. Turn the current off and measure the brightness again.

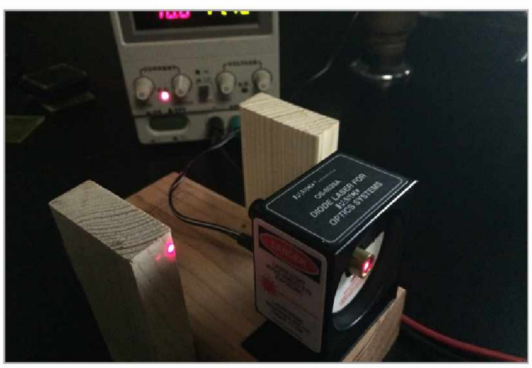
Questions:

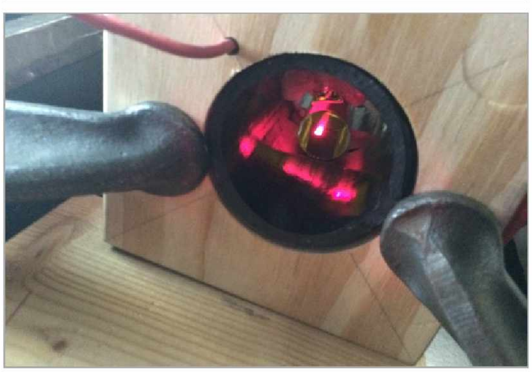
25. Was there any significant difference in the brightness measurements?
26. If there is a significant difference in measurements, is a more complete data set (from 0 to 180, or 90 to 270) warranted?
27. If warranted, measure the brightness from 90 to 270 degrees in 10 degree increments with both the field on, and field off.
28. Plot the two sets of data points on a new graph.
29. By how many degrees are the two graphs separated?


The Faraday Effect - Lab
Instrumentation
laser power
On
Off
amps
polarizer angle
faraday rotator
flint glass
Submit

Lab Cams







Plans for Deployment and Dissemination

During the summer of 2015, the Physics Department purchased six glass cylinders with optical properties that I provided. The intent of the Department is to use my plans as a basis for an undergraduate lab to study the Faraday Effect. It would be scientifically and pedagogically interesting to obtain two more lasers (a green and blue laser), to test out polarized light at wavelengths shorter than red, and the Physics Department is considering some commercial sources which I researched.

The next likely step, however, would be to seek out funding and some interested talent from the College of Engineering and Mines and begin work on a mechanical-robotic interface which would take the lab into RCL status. One of the faculty members from the UAF College of Engineering and Mines shared the view that such a project would make a good senior level undergraduate project and was willing to look into the development plans more closely.

Reflections on the Process

Creating a lab is a very difficult process. The realities of the lab bench area with power, lighting, temperature and space constraints readily becomes apparent. Creating a lab suitable for instruction is a job in and of itself. Just procuring the parts suitable for lab investigations is a very time intensive effort. Although I was not successful in creating a viable instruction lab due to materials and equipment, I did craft the plans that would allow me or someone else to take this project further. I have raised the prospect of senior engineering students working on the robotic and electronic apparatus that would bring the existing lab to RCL level. This idea was deemed workable and its possible that some stages of this development would make a perfect senior level undergraduate project.

Thinking about the physical constraints also brings to mind the instructional constraints. If theory is presented one way, it might be too simplistic for some students, or use mathematical terms which are unfamiliar. I think creating a lab is an extremely good activity for any instructional designer to undertake because of the complexity of the task and the requirements for attention to detail. The theoretical and procedural material that I created for this lab was aimed at the undergraduate level. Someone else could create background material and exercises for high school students or the general public.

References

Abdulwahed, M., & Nagy, Z. K. (2009). Applying kolb's experiential learning cycle for laboratory education. *Journal of Engineering Education*, *98*(3), 283-294. Retrieved from EBSCO Host.

Abu-Taha, M. I., Halasa, M. A., & Abu-Samreh, M. M. (2013). On the usage of the faraday effect as an authentication technique for vegetable oils. *Journal of Modern Physics*, *04*(02), 230-235. doi:10.4236/jmp.2013.42032

ALMA Reveals Intense Magnetic Field Close to Supermassive Black Hole. (2015, April 16). *eso1515*. Retrieved from http://www.eso.org/public/news/eso1515/

Andujar, J. M., Mejias, A., & Marquez, M. A. (2011). Augmented reality for the improvement of remote laboratories: An augmented remote laboratory. *IEEE Transactions on Education*, *54*(3), 492-500. doi:10.1109/TE.2010.2085047

Baran, J., Currie, R., & Kennepohl, D. (2004). Remote instrumentation for the teaching laboratory. *Journal of Chemical Education*, *81*(12), 1814-1816.

Bates, T. (2013). Can you teach lab science via remote labs? *Online learning and distance education resources* [Web page]. Retrieved from www.tonybates.ca: http://www.tonybates.ca/2013/04/22/can-you-teach-lab-science-via-remote-labs/

Cagiltay, N. E., Aydin, E., Aydin, C. C., Kara, A., & Alexandru, M. (2011). Seven principles of instructional content design for a remote laboratory: A case study on ERRL. *IEEE Transactions on Education*, *54*(2), 320-327. doi:10.1109/TE.2010.2058115

Cardoso, A., Vieira, M., & Gil, P. (2012). A remote and virtual lab with experiments for secondary education, engineering and lifelong learning courses. *Int. J. Onl. Eng.*, *8*(S2). doi:10.3991/ijoe.v8is2.1984

Carroll, J. M., & Rosson, M. (1987). The paradox of the active user. In Carroll, John M (Ed.), *Interfacing thought: Cognitive aspects of human-computer interaction.* The MIT Press.

Druyan, A., Sagan, C., & Soter, S. (2014). The electric boy. In *Cosmos: A spacetime odyssey.*

Eckert, B., Gröber, S., & Jodl, H. -J. (2009). Distance education in physics via the internet. *American Journal of Distance Education*, *23*(3), 125-138. doi:10.1080/08923640903076735

Feig, A. D. (2010). An online introductory physical geology laboratory: From concept to outcome. *Geosphere*, *6*(6), 942-951. doi:10.1130/GES00511.1

Gomes, L., & Bogosyan, S. (2009). Current trends in remote laboratories. *IEEE Transactions on Industrial Electronics*, *56*(12), 4744-4756. doi:10.1109/TIE.2009.2033293

Gröber, S., Vetter, M., Eckert, B., & Jodl, H. J. (2007). Experimenting from a distanceremotely controlled laboratory (RCL). *European Journal of Physics*, *28*(3), S127. Retrieved from Google Scholar.

Jona, K., & Vondracek, M. (2013). A remote radioactivity experiment. *The Physics Teacher*, *51*(1), 25. Retrieved from Google Scholar.

Ku, H., Ahfock, T., & Yusaf, T. (2011). Remote access laboratories in australia and europe. *European Journal of Engineering Education*, *36*(3), 253-268. doi:10.1080/03043797.2011.578244

Lang, D., Mengelkamp, C., Jäger, R. S., Geoffroy, D., Billaud, M., & Zimmer, T. (2007). Pedagogical evaluation of remote laboratories in emerge project. *European Journal of Engineering Education*, *32*(1), 57-72. doi:10.1080/03043790601055626

Maki, J., Thiessen, D., Pourangi, A., Kobzeff, P., Litwin, T., Scherr, L., . . . Maimone, M. (2012). The mars science laboratory engineering cameras. *Space Science Reviews*, 2012. doi:10.1007/s11214-012-9882-4

Peters, E. (2005). Reforming cookbook labs. *Science Scope*, *29*(3), 16-21. Retrieved from EBSCO Host.

Polarization (waves). (n.d.). Polarization (waves). [Web page]. Retrieved from https://en.wikipedia.org/wiki/Polarization_(waves)

Preston, D. W., & Dietz, E. R. (1991). *The art of experimental physics*. New York: Wiley.

Sabella, M. S., Coble, K., & Bowen, S. P. (2008). Using the resources of the student at the urban, comprehensive university to develop an effective instructional environment. In M. Henderson, M. Sabella, & L. Hsu (Eds.), *2008 Physics Education Research Conference:* (pp. 42-45). American Institute of Physics. doi:10.1063/1.3021269

Sajo-Bohus, L., Greaves, E. D., Barros, H., Gonzalez, W., & Rangel, A. (2007). LabView™ based nuclear physics laboratory experiments as a remote teaching and training tool for latin american educational centers. *AIP Conference Proceedings*, *947*(1), 477-478. doi:10.1063/1.2813859

Sauter, M., Uttal, D. H., Rapp, D. N., Downing, M., & Jona, K. (2013). Getting real: The authenticity of remote labs and simulations for science learning. *Distance Education*, *34*(1), 37-47.

Scheduling a Lab - Students | Western Interstate Commission for Higher Education. (2015). [Web page]. Retrieved from www.wiche.edu: http://www.wiche.edu/nanslo/creative-science-solutions/students-scheduling-labs

Schissel, D. P., Abla, G., Humphreys, D. A., Penaflor, B. G., Sammuli, B. S., & Walker, M. L. (2009). Remote control of a fusion facility. *Fusion Engineering & Design*, 1729-1733. doi:10.1016/j.fusengdes.2009.02.041

Shakir, A. A., AL-Mudhafa, R. D., & Al-Dergazly, A. A. (2013). Verdet constant measurement of olive oil for magnetic field sensor. *International Journal of Advances in Electrical and Electronics Engineering*, *2*(3), 362-368. Retrieved from http://www.sestindia.org/volume-ijaeee/.

Suchat, S., Viriyavathana, P., Jaideaw, P., Haisirikul, N., Kerdsang, W., & Petcharavut, S. (2011). Progress in electromagnetics research symposium proceedings. In *Measurement of the verdet constant in different mediums by using ellipsometry technique* (pp. 803-806). Suzhou, China.

Tipping, T. N. (2011). Educational activities at the nuclear engineering teaching laboratory. *AIP Conference Proceedings*, *1336*(1), 742-743. doi:10.1063/1.3586201

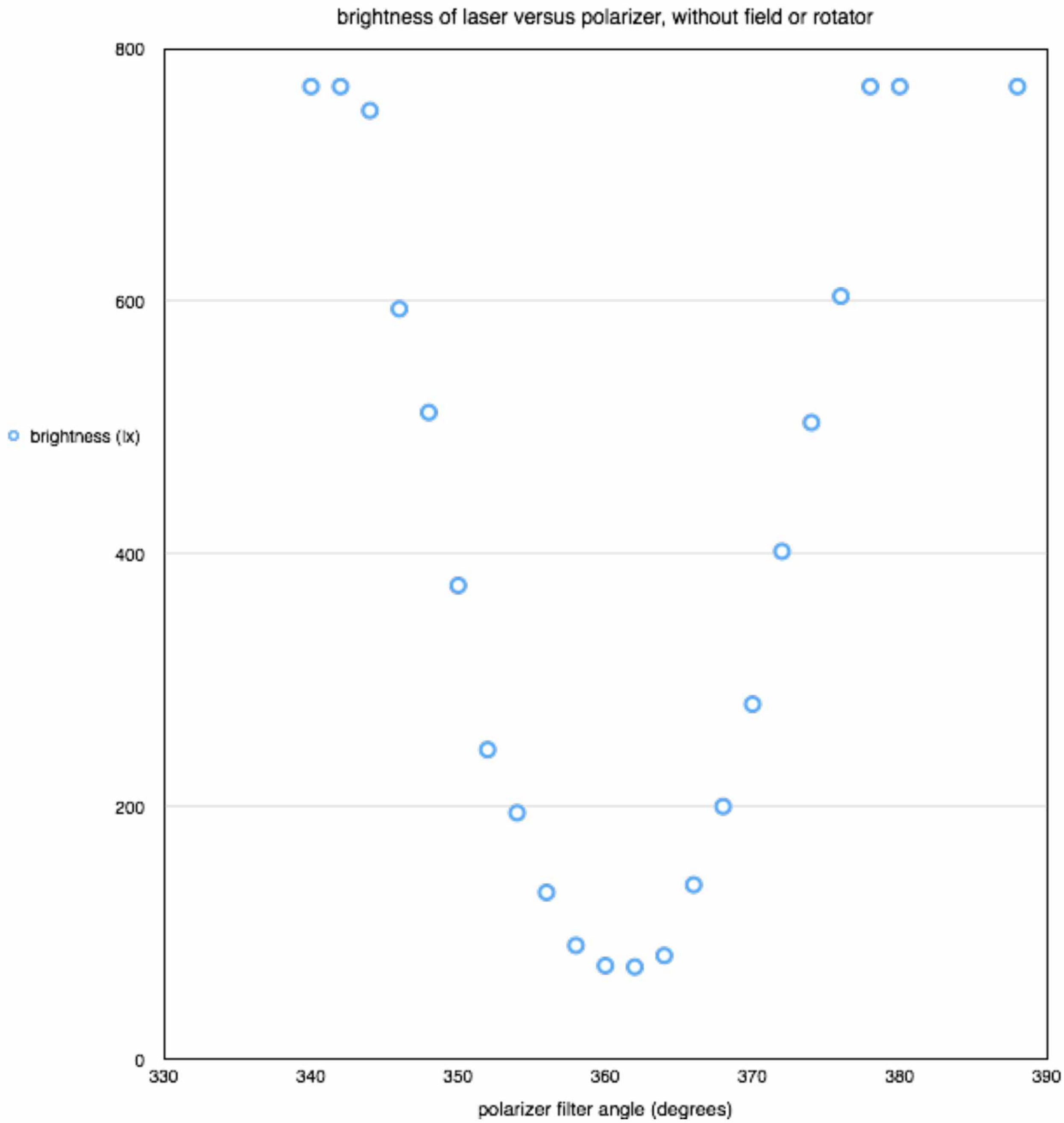
Van Der Meij, H. (2007). Goal-Orientation, goal-setting, and goal-driven behavior in minimalist user instructions. *IEEE Transactions on Professional Communication*, *50*(4), 295-305.

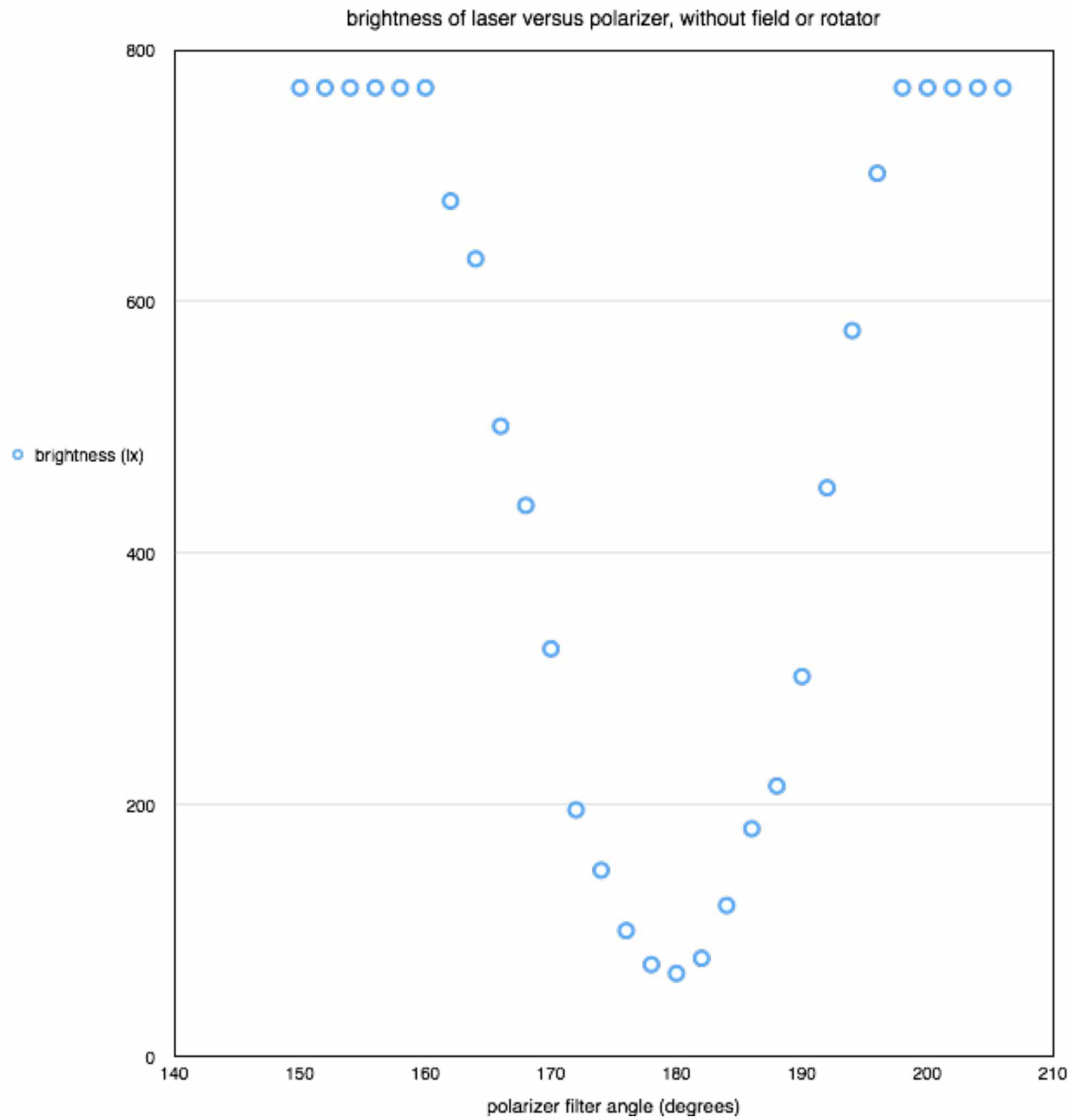
Verdet Constant. (n.d.). Verdet constant. [Web page]. Retrieved from https://en.wikipedia.org/wiki/Verdet_constant

Appendix A

brightness of laser versus polarizer, without field or rotator

degree	lux (lx)	degree	lux (lx)		
340	770	150	770		
342	770	152	770		
344	751	154	770		
346	594	156	770		
348	512	158	770		
350	375	160	770		
352	245	162	680		
354	195	164	634		
356	132	166	501		
358	90	168	438		
360	74	170	324		
362	73	172	196		
364	82	174	148		
366	138	176	100		
368	200	178	73		
370	281	180	66		
372	402	182	78		
374	504	184	120		
376	604	186	181		
378	770	188	215		
380	770	190	302		
388	770	192	452		
		194	577		
		196	702		
		198	770		
		200	770		
		202	770		
		204	770		
		206	770		

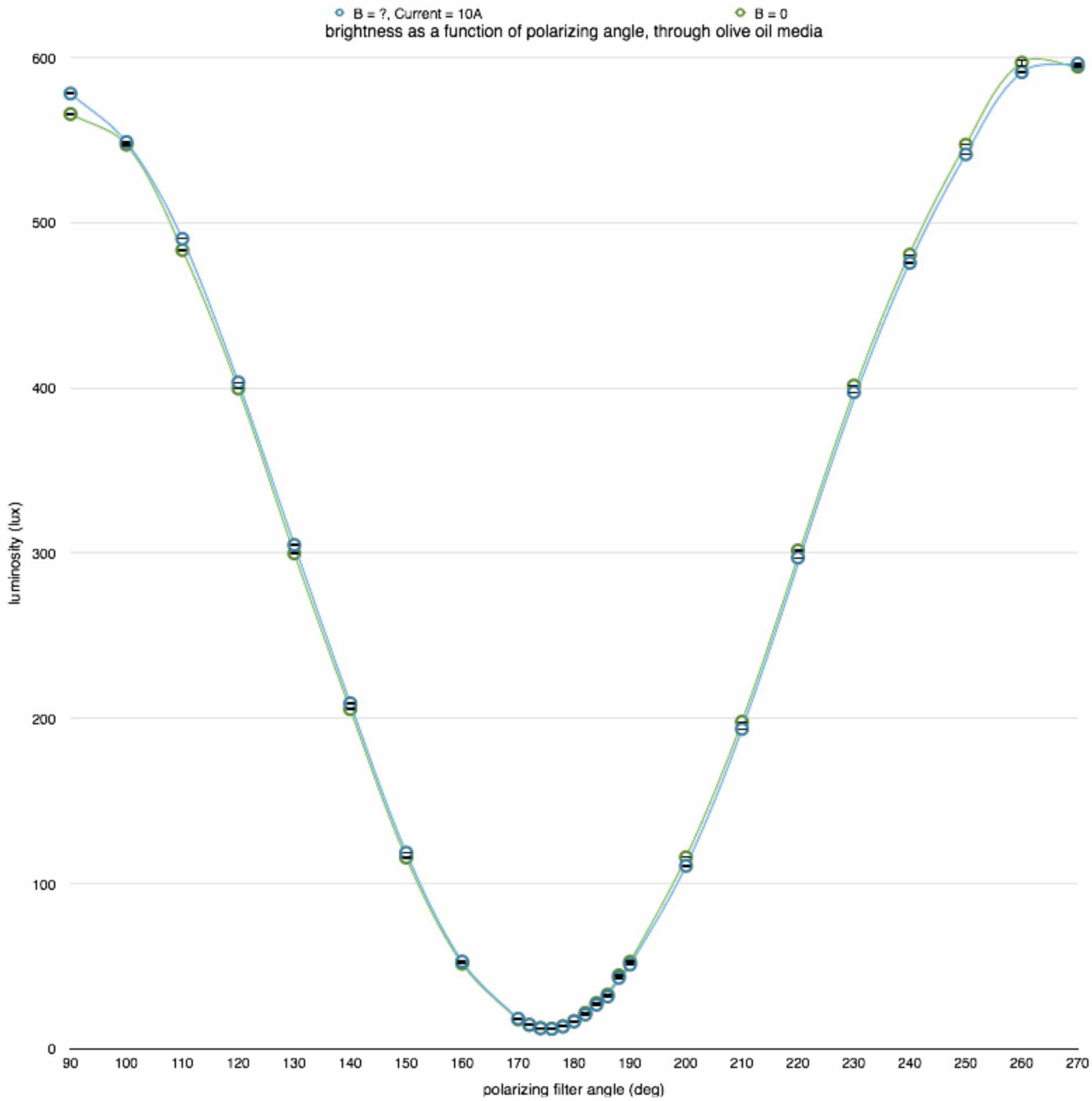

brightness of laser versus polarizer, without field or rotator
800
600
400
200
0
brightness (lx)
330
340
350
360
370
380
390
polarizer filter angle (degrees)


brightness of laser versus polarizer, without field or rotator
800
600
400
200
0
brightness (lx)
140
150
160
170
180
190
200
210
polarizer filter angle (degrees)

Appendix B

brightness of laser versus polarizer angle, through olive oil media with and without a magnetic field B induced by 10A through my solenoid coil

		c	d	e	f
		B = 0		B = ?, Current = 10A	
	polarizing angle	mean luminosity (lux)	std. dev.	mean luminosity (lux)	std. dev
4	90	565.7	0.91	578.1	0.75
	100	547.2	0.79	548.8	0.74
	110	483.4	0.55	490.2	0.77
	120	399.6	0.31	403.3	0.36
	130	299.8	0.63	304.9	0.18
	140	205.5	0.14	209.1	0.15
	150	115.7	0.17	118.7	0.16
	160	51.5	0.10	52.8	0.11
12	170	17.7	0.09	18.2	0.10
	172	14.3	0.09	14.6	0.08
	174	12.6	0.11	12.4	0.09
	176	12.1	0.08	12.0	0.05
	178	13.6	0.12	13.4	0.13
	180	16.8	0.09	16.5	0.09
	182	21.7	0.1	20.7	0.09
	184	27.7	0.12	26.6	0.11
	186	32.8	0.12	31.6	0.09
	188	44.4	0.18	42.9	0.14
	190	52.6	0.11	50.9	0.11
23	200	115.9	0.22	110.7	0.39
	210	197.9	0.26	193.5	0.38
	220	301.6	0.29	297.2	0.36
	230	401.4	0.59	397.3	0.40
	240	480.6	0.59	475.6	0.47
	250	547.2	0.63	541.3	0.47
	260	596.8	0.61	591.0	2.04
30	270	594.4	0.48	596.2	0.80


B = ?, Current = 10A
B = 0
brightness as a function of polarizing angle, through olive oil media
luminosity (lux)
600
500
400
300
200
100
0
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
polarizing filter angle (deg)